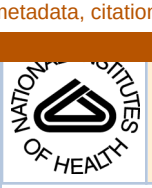

Published in final edited form as:

Atmos Environ. 2013 February 1; 66: 145–150. doi:10.1016/j.atmosenv.2012.06.087.

Presence of organophosphorus pesticide oxygen analogs in air samples

Jenna L. Armstrong[1], **Richard A. Fenske**[1], **Michael G. Yost**[1], **Kit Galvin**[1], **Maria Tchong-French**[1], and **Jianbo Yu**[1,2]

[1]Department of Environmental and Occupational Health Sciences, University of Washington School of Public Health, Seattle, WA, Health Sciences Building, 1959 NE Pacific Street, Box 357234, Seattle, WA 98195

[2]Environmental Health Laboratory and Trace Organics Analysis Center, University of Washington, Seattle, WA, Health Sciences Building F455, 1959 NE Pacific Street, Seattle, WA 98195

Abstract

A number of recent toxicity studies have highlighted the increased potency of oxygen analogs (oxons) of several organophosphorus (OP) pesticides. These findings were a major concern after environmental oxons were identified in environmental samples from air and surfaces following agricultural spray applications in California and Washington State. This paper reports on the validity of oxygen analog measurements in air samples for the OP pesticide, chlorpyrifos. Controlled environmental and laboratory experiments were used to examine artificial formation of chlorpyrifos-oxon using OSHA Versatile Sampling (OVS) tubes as recommended by NIOSH method 5600. Additionally, we compared expected chlorpyrifos-oxon attributable to artificial transformation to observed chlorpyrifos-oxon in field samples from a 2008 Washington State Department of Health air monitoring study using non-parametric statistical methods. The amount of artificially transformed oxon was then modeled to determine the amount of oxon present in the environment. Toxicity equivalency factors (TEFs) for chlorpyrifos-oxon were used to calculate chlorpyrifos-equivalent air concentrations. The results demonstrate that the NIOSH-recommended sampling matrix (OVS tubes with XAD-2 resin) was found to artificially transform up to 30% of chlorpyrifos to chlorpyrifos-oxon, with higher percentages at lower concentrations (< 30 ng/m3) typical of ambient or residential levels. Overall, the 2008 study data had significantly greater oxon than expected by artificial transformation, but the exact amount of environmental oxon in air remains difficult to quantify with the current sampling method. Failure to conduct laboratory analysis for chlorpyrifos-oxon may result in underestimation of total pesticide concentration when using XAD-2 resin matrices for occupational or residential sampling. Alternative methods that can accurately measure both OP pesticides and their oxygen analogs should be used for air sampling, and a toxicity equivalent factor approach should be used to determine potential health risks from exposures.

Keywords

air monitoring; exposure; organophosphorus pesticides; oxon; toxicity equivalent concentration; XAD resin

1. Introduction

Although banned for residential use in 2000, the common organophosphorus pesticide chlorpyrifos (CPF) remains an effective tool for agricultural protection from more than 200 pests. CPF continues to be widely used because few chemical substitutes are as effective. In Washington State, CPF is often applied in aerosolized form to tree fruits and vegetables using a large sprayer attached behind a tractor. A number of past studies have found that some semi-volatile organophosphorus pesticides (OP) can drift in air far from source of application, as indicated in past community studies (see Table 1). Recent monitoring in the agricultural regions of California and Washington have reported both the parent compound (CPF) and the presence of chlorpyrifos-oxon (CPF-O), the oxygen analog of CPF, in community air samples.

The airborne presence of the oxons of OP pesticides is a human health concern because *in vivo* toxicity studies have found that the toxicity of the oxon can be 5 to 100 times more toxic than the parent OP pesticide (Chambers and Carr 1993; Cole et al 2005; 2011, Huff et al. 1994, Timchalk et al. 2007). CPF-O is believed to pose a special risk for genetically susceptible individuals who have lower levels of the paraoxonase [PON-1(−/−)] enzyme playing a key role in metabolism of OPs in the body. In addition, young mice have been found to demonstrate changes in specific brain cells and irregular distribution of neurons in the cortical plate after exposures to chronic low doses of CPF-O (Furlong et al. 2005). The presence of oxon in community air samples is a concern because children may be particularly susceptible to its toxicity (Harnly et al. 2005, Costa et al. 2005) due to differences in metabolic functioning during development.

CPF-O may be present in the atmospheric environment, as the transformation of OP pesticides to their oxons has been documented for foliar residues (Popendorf and Leffingwell 1978; Spear et al. 1978) and in air samples (Seiber et al. 1989). The environmental formation of oxons has been attributed to conditions such as higher temperatures, ozone, dry weather, or photodegradation via ultraviolet light (Spear et al. 1978; Aston and Seiber 1997; Bavcon Kralj et al. 2007). Very little is known about transformation or changes in levels of CPF-O as the total pesticide mixture drifts from site of application to more residential areas.

CPF-O was identified in virtually all of the 145 air samples collected in agricultural communities of the recent 2008 Washington State Department of Health air monitoring study (Fenske et al. 2009), with higher proportions oxon being reported at residential locations >250 m from agricultural fields. This was a concern for public health because the study area is home to many farmworker families, and greater than a third of the population consists of children and adolescents <18 years of age (US CENSUS 2010). The oxon represented as much as 94% percent of the total CPF in some cases; this raised the issue of potential transformation during air sampling. It is important to rule out sampling transformation in order for researchers to correctly assess health risk from exposure to airborne CPF-O.

The 2008 Washington study used OSHA Versatile Sampling (OVS) tubes, a popular sampling matrix that contains XAD-2 resin. The OVS tube is part of the standard method

recommended by the National Institute for Occupational Safety and Health (NIOSH 1994), and the XAD-2 resin is identified in current guidance documents as an appropriate sampling matrix by the U.S. Environmental Protection Agency and the American Society for Testing and Materials (USEPA 1999; ASTM 2011). The resin has been used in a large number of community and occupational air sampling studies (Table 1).

The primary objective of this study was to determine the degree to which the OP pesticide chlorpyrifos (CPF) can be transformed artificially to its oxygen analog form by air sampling with OVS tubes at levels representative of concentrations measured during community sampling at low and high flow rates. The second objective was to ascertain the extent to which CPF-O may have been environmentally present in the community air that was sampled in the 2008 Washington study. The final objective was to use this data to include the toxicity of CPF-O and estimate potential changes in community health risk resulting from respiratory exposure to the mixture of both parent CPF and CPF-O.

2. Sampling Methods

2.1 Laboratory Studies

Sampling was conducted according to NIOSH method 5600 for OP pesticides (NIOSH, 1994). OVS tubes containing XAD-2 sorbent were spiked in triplicates at levels of 0, 42, 210, and 2100 ng of 99.5% pure chlorpyrifos (ChemService, Inc. PS-674) in solution. A 25 μl Hamilton™ positive displacement syringe was used to apply chlorpyrifos in acetone solution directly to the resin by inserting the needle beyond the quartz fiber pre-filter into the first bed of XAD-2. The back-up XAD-2 resin was not spiked because past studies have demonstrated that even higher concentrations of chlorpyrifos (>96%) are primarily trapped on the first resin bed (Shibamoto et al. 1996). Each OVS tube was paired with an SKC air sampling pump (224-PCXR8) operated at a flow rate of either two or six liters per minute (LPM) for approximately 24 hours. Two flow rates were tested to examine potential differences in artificial transformation at higher flow rates and to simulate popular air sampling procedures conducted in past community monitoring studies (CARB 1998, CDPR 2003, Fenske et al 2009). Larger spike masses were applied at higher flow rates (~6LPM) to account for larger air sampling volumes. Pumps were pre- and post-calibrated between studies using a DryCal DC-Lite and flow rates were calculated separately for each sample in order to calculate the air volumes for each spiked sample. Laboratory blanks, spikes, and storage spikes were included in the experiments for quality assurance purposes.

2.2 Field Studies

The following spring, data were collected outdoors at a community air sampling site managed by the Washington Department of Ecology in Yakima Valley, WA. The site was previously utilized in the 2008 Washington State study to collect ambient concentrations and is located >1 km (1405 m) from the nearest tree fruit field. OVS tubes containing XAD-2 sorbent were spiked with chlorpyrifos in triplicates at levels of of 0, 15, 30, 60, 200, 592, and 2628 ng following the procedures described in the laboratory studies. Previous data from the 2008 study emphasized the need to control for small background concentrations of CPF and CPF-O by including non-spiked samples. Triplicate spikes of 0 and 30 ng were deployed with no pump air flow. All SKC air sampling pumps were stored in a weather-proof container and operated at either 2 or 6 LPM for 24 hours. Outdoor temperatures ranged from 4–12°C during the sampling period. Samples were stored at a University of Washington field office in Yakima in a freezer at −10°C until transport to the University of Washington Environmental Health Laboratory. Flow rates were calibrated and calculated separately in order to calculate the air volumes (m^3) for each spiked sample.

The Environmental Health Laboratory performed chemical analysis for both CPF and CPF-O. A new LC-MS-MS method was developed through modifications of methods described by Sancho et al. (2000), Yusa et al. (2009), and NIOSH Method 5600. The quartz fiber filter and primary resin section was placed in a 10 mL vial, and separated from the secondary resin section to analyze for break-through. All samples were sonicated with an acetone/acetonitrile solution containing stable-isotope labeled internal standards of chlorpyrifos diethyl-D_{10}, 99% (Cambridge Isotope Labs DLM-4360) and $_{13}C_2$, $_{15}N$-Chlorpyrifos oxon (donated by Dow Agro Sciences LLC). The limit of detection (LOD) for both chlorpyrifos and CPF-O was 1 ng/sample. Fortification/recovery studies involved spiking matrix blanks with CPF and CPF-O at levels ranging from 5 to 1000 ng/sample; recoveries were 86.1 – 94.6% for CPF and 85.8 – 97.6% for CPF-O.

Quality assurance field spikes and blanks were carried into the field and handled in a manner similar to other samples except they were capped and did not have air drawn through them. Field spikes were prepared by introducing low levels CPF (20–50 ng/sample) into the front section of the XAD-2 resin with a micropipette, immediately recapping, followed by storage on ice. Field spike recoveries were 74.4 –101.5% for CPF, and yielded no detectable CPF-O. Field blanks yielded no CPF or CPF-O. Static storage spikes were kept in the laboratory freezer at −10°C for 2 months and recoveries ranged from 84–105%.

2.3 Determination of artificial and environmental CPF-O

Total chlorpyrifos was calculated for each sample by converting the measured chlorpyrifos-oxon to its chlorpyrifos equivalent using the ratio of molecular weights, and adding this value to the measured chlorpyrifos, as indicated in Equation 1:

$$CPF_{Total} = CPF{-}O_m{}^{*}(CPF_{MW}/CPF{-}O_{MW}) + CPF_m \quad \text{(Equation 1)}$$

Where CPF_{Total} = total chlorpyrifos in sample (ng), CPF-O_m = mass of chlorpyrifos-oxon measured in sample (ng), CPF_{MW} = chlorpyrifos molecular weight (350.6 ng/nmol), CPF-O_{MW} = chlorpyrifos-oxon molecular weight (334.5 ng/nmol), and CPF_m = mass of chlorpyrifos measured in the sample (ng). To control for small concentrations levels of CPF and CPF-O, outdoor recovery masses were corrected by subtracting background levels CPF and CPF-O from non-spiked samples in the outdoor environment to calculate total % recovery and % CPF-O.

The percent chlorpyrifos-oxon (% CPF-O) in each sample was calculated by dividing the mass of chlorpyrifos-oxon, expressed as chlorpyrifos equivalent, by total chlorpyrifos and multiplying by 100, as indicated in Equation 2:

$$\%\ CPF{-}O = CPF{-}O_m{}^{*}(CPF_{MW}/CPF{-}O_{MW})/CPF_{Total}{}^{*}100 \quad \text{(Equation 2)}$$

Next, % CPF-O (y-axis) was plotted against total mass per unit volume (x-axis), which was estimated by dividing CPF_{Total} by specific air sampling volumes. A quadratic prediction plot with 95% confidence intervals was used to model expected oxon as an artifact of sampling (R^2 = 0.288) as a function of total CPF air concentration. Community measurements from ambient sites (> 500 m from orchard) and near-field sites (< 100 m from orchard) from the 2008 Washington State study were directly compared with the laboratory and field experimental data. A non-parametric statistical test was used compare expected values determined from laboratory and field study samples to observed community measurements from Washington State study data. The Mann Whitney U-test was used since sample size and variability of the two groups differed and the observations were independent of each other (Fay and Proschan 2010). The basic assumption of normality was questionable via

Shapiro Wilk test and small experiment sample size(Rosner and Grove 1999). Due to the variable nature of the relationship between oxon transformation and total concentration chlorpyrifos, statistical tests were performed for the entire data set and for each data tertile of pesticide concentrations. All calculations were performed using STATA™ 10.1 data analysis and statistical software (StataCorp LP College Station, Texas).

3. Results

Data from the laboratory and field experiments are presented in Table 2. In the laboratory experiments, samples with low spike masses CPF (42 ng) had an average of 31.6% oxon transformation whereas higher spike masses CPF (~2100 ng) had an average of only 15.4% oxon transformation. Similarly in the field experiments, low spike masses (<30 ng) yielded an average of 24.4% oxon, whereas medium spike masses (60–200 ng) yielded only 9.9% oxon. A similar effect was found at higher flow rates of 6 LPM. Samples hung outdoors with no flow rate (0 LPM) resulted in no conversion to CPF-O. These results further emphasized that artificial transformation was occurring during the action of pulling air through the sampling tube.

An inverse relationship was observed in both the laboratory and field study experiments between total chlorpyrifos expressed as a mass per unit volume (ng/m^3) and the proportion of chlorpyrifos transformed to oxon on the XAD-2 resin sampling matrix (Figure 1). A quadratic prediction plot model accounted for about 29% of the variability in these data ($R^2 = 0.288$). The 95% confidence intervals were generated from the model to assess differences between the transformation experiments and the 2008 Washington State study. In many instances the proportion of oxon found in the 2008 air monitoring samples exceeded the upper 95% C.I. of the experimental data. This was especially true at low concentrations (≤10 ng/m^3) and in ambient samples that were located > 500 meters from the nearest orchard. In fact, more than half (69%) of the ambient samples (n=32) were higher than the predicted artificial transformation values. These samples warrant further investigation because this means significant airborne CPF-O in residential air. On the other hand, some of the percent oxon was less than expected at medium concentrations and in near-field samples < 100 meters of an orchard. Only 36% of near-field samples (n = 113) had higher percentages chlorpyrifos-oxon than predicted. Higher proportions CPF-O in the air samples farther in proximity from fields may be attributable to physiochemical transformation as pesticides drift further from their source of application. In the past, atmospheric scientists have used the term “aging” to describe similar processes on the local/regional scale for complex mixes of pollutants and transformation products (Demerjian, 2011).

All the community samples from the Washington State study, both ambient and near-field, had a median of 14% greater proportion oxon (95 C.I. 12.8 –20.3%) than could be explained by the artificial transformation experiments in the laboratory and field. This difference was statistically significant in a Mann Whitney test ($\alpha < 0.005$). When broken into tertiles (Figure 2), the Washington study had a 15% greater proportion of oxon than expected (95 C.I. 10.04– 18.9%; $\alpha < 0.001$) at low concentrations (<10ng/m^3) and 10% greater proportion of oxon than expected (95 C.I. 4.8 to 16.97%; $\alpha = 0.005$) at medium concentrations (10–30 ng/m^3). The opposite was true for higher concentrations (>30 ng/m^3); the Washington study actually had 3% less proportion of oxon than expected, but this was not statistically significant (95 C.I. −7.85 to 12.7%; $\alpha = 0.401$).

4. Discussion

4.1 Artificial Transformation

In this study we found that CPF is artificially transformed on XAD-2 resin to CPF-O, but that it does not account for all CPF-O measured in the air of an agricultural community. This transformation is a major concern because Agency for Toxic Substances and Disease Registry (ATSDR) currently recommends the use of XAD-2 resin air sampling matrices. ATSDR notes that CPF may be converted to its oxygen analog under certain environmental conditions; however, it does not discuss the potential for artificial production of the oxon on the sampling matrix (ASTM, 2011). Neither the EPA/ASTM D 4861 international method nor the NIOSH 5600 method makes any mention of measuring for CPF-O. This study has demonstrated that if the oxon in air samples using XAD-2 resins is not measured, then true CPF air concentrations maybe underestimated by 5–30%.

Woodrow et al. (1978) noted the conversion of parathion to paraoxon on Amberlite XAD-4 resins during one-hour laboratory testing at high air sampling volumes and Seiber et al. (1989) also reported substantial conversion (up to 54%) of methyl parathion to its oxygen analog on XAD. In 1996, the California Air Resources Board (CARB) found substantial amounts of CPF-O in many of the samples collected in Tulare County (1998a; 1998b). CARB reported that when using XAD-4 resin, “conversion of chlorpyrifos to the oxon analogue may take place on the trapping media during sampling.” However, CARB also reported that concurrent field spike studies showed “only insignificant conversion taking place under actual field conditions.” These results are puzzling in light of our finding of significant conversion of CPF to its oxon on XAD-2 resin in both the laboratory and in the field.

The act of drawing air through the sampling resin may be a causal factor, as demonstrated by no conversion in XAD resin at zero flow rate (Table 2). In the future, it will be important to test new sampling matrices or examine passive methods using diffusion or deposition to measure CPF and CPF-O in air. Arcury et al (2006) have noted that many researchers and safety personnel continue to collect airborne OP pesticide samples without any harmonized environmental sampling and chemical analysis methods. Not only do problems exist with the current method, there is also a need for new guidelines on how to collect and measure both organophosphate pesticides and their oxygen analogs with minimal sampling artifacts.

4.2 Environmental Chlorpyrifos-Oxon (CPF-O)

A direct comparison to the 2008 Washington State study has also demonstrated that transformation of OP pesticides to their oxygen analogs may still be occurring in the atmospheric environment. Under these circumstances, the health risk associated with exposure to airborne OP pesticides will be higher than previously estimated due to increased potency of CPF-O in the airborne mixture.

We have demonstrated this phenomenon by using toxicity equivalence factor (TEF) values, which have been used in the past for compounds such as polychlorinated biphenyls (PCBs) and dioxins (Van den Berg et al 1998) in chemical risk assessment. These numbers are drawn two main *in vivo* toxicology studies that conducted side-by-side comparisons of brain acetylcholinesterase inhibition for both CPF and CPF-O (Chambers and Carr 1993; Cole et al. 2005).

A toxicity equivalent concentration (TEC) can be calculated for the mixture of CPF and CPF-O by adjusting for the toxicity of the oxon formed in the environment and available for inhalation:

$$TEC_{CPF} = (CPF{-}O_e * CPF_{MW} / CPF{-}O_{MW} * TEF) + CPF \quad \text{(Equation 3)}$$

Where TEC = toxicity equivalent concentration of chlorpyrifos parent and oxon; CPF-O_e = mass of environmental chlorpyrifos-oxon; CPF_{MW} = molecular weight of chlorpyrifos (350.6 ng/nmol); CPF-O_{MW} = molecular weight of chlorpyrifos-oxon (334.5 ng/nmol); TEF = toxicity equivalence factor drawn from toxicology studies; and CPF = chlorpyrifos measured in the sample (ng).

In Table 3, we illustrate the possible magnitude of changes in toxicity from respiratory exposure to mixtures of the parent CPF and CPF-O. We conclude that even at low concentrations CPF-O (e.g., 2 ng/m^3), total toxicity can be increased by factors of one to ten. If the higher toxicity equivalence factor values are correct, then toxicity could increase by more than 20-fold, putting some deceptively “low” concentrations above the acute screening level of 1,200 ng/m^3 as defined by the California EPA (CDPR 2006).

Since many families in central Washington State live in communities with high agricultural density, we have found that pesticide levels with high amounts CPF-O (>30 ng) would be a concern to human health. Neither artificial transformation nor toxicity equivalence of CPF-O was taken into account for the 2008 air monitoring study. Given its high potency, the failure to include analysis for CPF-O in air samples this could lead to considerable underestimates of health risk, especially when considering populations of genetically susceptible individuals and young children.

Future research should continue to investigate the sources and causes of oxon formation in dusts and airborne particles, such as “aging”, mixtures, photodegradation, temperature, and the presence of oxidizing compounds such as ozone (O_3) and sulfur dioxide (SO_2). Ozone levels in particular have been predicted to increase substantially in areas like central Washington State as a result of changes in the atmosphere and climate. Although ozone is known to damage vegetation and reduce crop yields, less is known about its potential airborne chemical interactions with pesticides and may become an increasing concern with climate change patterns.

These results will contribute to the much needed explanation of environmental fate and transport of CPF-O to complement recent toxicological and epidemiological studies that have examined numerous health effects. These experiments stress the importance of accurately defining oxon presence in the environment because low concentrations may change health risk assessments—especially at concentrations typical for residential atmospheres farther from agricultural fields, where many families and children live, work and play. These findings call for consideration of the presence of organophosphorus oxons in air when calculating residential risk to pesticide drift and aerial transport.

Acknowledgments

This work was supported by the NIOSH Educational and Research Center Grant NIOSH-T42OH00843 and the Child Health Center Pesticide Exposures Pathways Project at the Center for Child Environmental Risks Research NEIHS-P01 ES009601, EPA-RD-83451401. Thanks to Lucio Costa, PhD for consultation on toxicity estimates.

References

Arcury T, Quandt S, Barr D, Hoppin J, McCauley L, Grzywacz J, Robson M. Farmworker exposure to pesticides: methodologic issues for the collection of comparable data. Environ Health Perspect. 2006; 114:923–928. [PubMed: 16759996]

ASTM. Standard Practice for Sampling and Selection of Analytical Techniques for Pesticides and Polychlorinated Biphenyls in Air. ASTM D4861-11. 2011 Annual Book of ASTM Standards: Volume 11.07, Atmospheric Analysis. (ASTM formerly known as American Society for Testing and Materials). 2011

Aston L, Seiber J. Fate of summertime airborne organophosphate pesticide residues in the Sierra Nevada Mountains. J. Environ. Qual. 1997; 26:1483–1492.

Bavcon Kralj M, Franko M, Trebš P. Photodegradation of organophosphorus insecticides – investigations of products and their toxicity using gas chromatography–mass spectrometry and AChE-thermal lens spectrometric bioassay. Chemosphere. 2007; 67:99–107. [PubMed: 17097717]

CARB. Report for the Application and Ambient Air Monitoring of Chlorpyrifos (and oxon analogue) in Tulare Country During Spring/Summer 1996. Sacramento, CA: California Air Resources Board; 1998 Apr 7.

CARB. Appendices for the Report for the Application and Ambient Air Monitoring of Chlorpyrifos (and the Oxon Analogue) in Tulare County during Spring/Summer, 1996. Sacramento, CA: California Air Resources Board; 1998a Apr 7.

CARB. Report for the Application (Kings County) and Ambient (Fresno County) Air Monitoring of Diazinon during Winter, 1998. C97-070/C97-069. Sacramento, CA: California Air Resources Board; 1998b.

CARB. Report for the Application and Ambient Air Monitoring of Malathion in Imperial County. C-98-003/C98-002. Sacramento, CA: California Air Resources Board; 1999.

CDPR. Report of Ambient Air Monitoring for Pesticides in Lompoc, California. Sacramento, CA: Department of Pesticide Regulation; 2003 Mar.

CDPR. Environmental justice pilot project: Pesticide air monitoring in Parlier, Second Progress Report. California Environmental Protection Agency, Department of Pesticide Regulation, December. Attachment IV discusses screening levels. 2006. http://www.cdpr.ca.gov/docs/envjust/pilot_proj/index.htm

CDPR. Pesticide Air Monitoring in Parlier, CA (Final Report). Sacramento, CA: California Department of Pesticide Regulation; 2009 Dec.

Chambers J, Carr RL. Inhibition patterns of brain acetylcholinesterase and hepatic and plasma aliesterases following exposures to three phosphorotionate insecticides and their oxons in rats. Toxicological Sci. 1993; 21:111–119.

Cole TB, Beyer RP, Bammler TK, Park SS, Farin FM, Costa LG, Furlong CE. Repeated developmental exposure of mice to chlorpyrifos oxon is associated with paraoxonase 1 (PON1)-modulated effects on cerebellar gene expression. Toxicol Sci. 2011; 123:155–169. [PubMed: 21673326]

Cole T, Walter B, Shih D, Tward A, Lusis A, Timchalk C, Richter R, Costa L, Furlong C. Toxicity of chlorpyrifos and chlorpyrifos oxon in a transgenic mouse model of the human paraoxonase (PON1) Q192 polymorphism. Pharmacogenet Genom. 2005; 15:589–598.

Costa L, Cole T, Vitalone A, Furlong C. Measurement of paraoxonase 1 (PON1) status as a potential biomarker for organophosphate toxicity. Clinica Chimica Acta. 2005; 352(1–2):37–47.

Curwin BD, Hein MJ, Sanderson WT, Nishioka MG, Reynolds SJ, Ward EM, Alavanja MC. Pesticide contamination inside farm and nonfarm homes. J Occup Environ Hyg. 2005; 2:357–367. [PubMed: 16020099]

Demerjian, K. Technical Challenges of Mulitpollutant Air Quality Management. Springer Science + Business Media; 2011. Atmospheric Science of Air Pollution Phenomena—Current Directions Toward Exposure Characterization; p. 231-259.

NIOSH. NIOSH Manual of Analytical Methods. 4th Edition. Cincinnati, OH: National Institute for Occupational Safety and Health; 1994. Pub. No. 94-113

Farahat FM, Fenske RA, Olson JR, Galvin K, Bonner MR, Rohlman DS, Farahat TM, Lein PJ, Anger WK. Chlorpyrifos exposures in Egyptian cotton field workers. Neurotoxicol. 2010; 31:297–304.

Fay M, Proschan M. Wilcoxon-Mann-Whitney or t-test? On assumptions for hypothesis tests and multiple interpretations of decision rules. Statistics Surveys. 2010; 4:1–39. [PubMed: 20414472]

Fenske, RA.; Yost, M.; Galvin, K.; Tchong, M.; Negrete, M.; Palmendez, P.; Fitzpatrick, C. Organophosphorus Pesticide Air Monitoring Project, Final Report. University of Washington:

2009. available from the Washington State Department of Health Pesticide Program. at http://www.doh.wa.gov/ehp/pest/uwdrift-report.pdf.

Furlong C, Cole T, Jarvik G, Pettan-Brewer C, Geiss G, Richter R, Shih D, Tward A, Lusis A, Costa L. Role of paraoxonase (PON1) status in pesticide sensitivity: genetic and temporal determinants. Neurotoxicology. 2005; 26:651–659. [PubMed: 16112327]

Harnly M, McLaughlin R, Bradman A, Anderson M, Gunier R. Correlating agricultural use of organophosphates with outdoor air concentrations: a particular concern for children. Environ Health Perspect. 2005; 113:1184–1189. [PubMed: 16140625]

Huff R, Corcoran J, Anderson M, Abou-Donia M. Chlorpyrifos oxon binds directly to muscarinic receptors and inhibits cAMP accumulation in rat striatum. J Pharmacol Exp Ther. 1994; 269:329–335. [PubMed: 7513360]

Jaipieam S, Visuthismajarn P, Siriwong W, Borjan M, Robson MG. Inhalation exposure of organophosphate pesticides by vegetable growers in the Bang-Rieng subdistrict in Thailand. J Environ Public Health. 2010 published online February 7.

LeNoir J, McConnell L, Fellers G, Cahill T, Seiber J. Summertime transport of current-use pesticides from California's Central Valley to the Sierra Nevada mountain range, USA. Env Tox and Chem. 1999; 18(12):2715–2722.

Peck A, Hornbuckle K. Gas-phase concentrations of current-use pesticides in Iowa. Env Sci Technol. 2005; 39(9):2952–2959. [PubMed: 15926538]

Popendorf W, Leffingwell T. Natural variations in the decay and oxidation of parathion foliar residues. J Agric Food Chem. 1978; 26:437.

Rosner B, Grove D. Use of the Mann-Whitney U-test for clustered data. Stat in Med. 1999; 18:1387–1400. [PubMed: 10399203]

Sancho J, Pozo O, Hernández F. Direct determination of chlorpyrifos and its main metabolite in human serum and urine by coupled column liquid chromatography/electrospray-tandem mass spectrometry. Rapid Commun Mass Spectrom. 2000; 14:1485–1490. [PubMed: 10931542]

Seiber J, McChesney M, Woodrow J. Airborne residues resulting from use of methyl parathion, molinate, and thiobencarb on rice in the Sacramento Valley, California. Environ Tox Chem. 1989; 8:577–588.

Shibamoto, T.; Mourer, C.; Hall, G.; Hengel, M. Method development, ambient site and application site monitoring for chlorpyrifos and chlorpyrifos oxon in air samples using XAD-4 resin as trapping medium. California Air Resources Board; 1996.

Spear R, Lee Y, Leffingwell J, Jenkins D. Conversion of parathion to paraoxon in foliar residues: effects of dust level and ozone concentration. J Agric Food Chem. 1978; 26:434.

Sultatos L, Costa L, Murphy S. Factors involved in the differential acute toxicity of the insecticides chlorpyrifos and methyl chlorpyrifos in mice. Toxicol App Pharmacol. 1982; 65:144–152.

Thomas KW, Dosemeci M, Hoppin JA, Sheldon LS, Croghan CW, Gordon SM, Jones ML, Reynolds SJ, Raymer JH, Akland GG, Lynch CF, Knott CE, Sandler DP, Blair AE, Alavanja MC. Urinary biomarker, dermal, and air measurement results for 2,4-D and chlorpyrifos farm applicators in the Agricultural Health Study. J Expo Sci Environ Epidemiol. 2010; 20:119–134. [PubMed: 19240759]

Timchalk C, Busby A, Campbell J, Needham L, Barr D. Comparative pharmacokinetics of the organophosphorus insecticide chlorpyrifos and its major metabolites diethylphosphate, diethylthiophosphate and 3, 5, 6-trichloro- 2-pyridinol in the rat. Toxicol. 2007; 237:145–157.

US CENSUS. United States Census Bureau. Washington, DC: 2010. http://2010.census.gov/2010census/

USEPA. [Accessed September 7, 2011] Method TO-10A: Determination Of Pesticides And Polychlorinated Biphenyls In Ambient Air Using Low Volume Polyurethane Foam (PUF) Sampling Followed By Gas Chromatographic/Multi-Detector Detection (GC/MD). Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air. United States Environmental Protection Agency. 1999. at http://www.epa.gov/ttnamti1/files/ambient/airtox/to-10ar.pdf.

Van den Berg M, Birnbaum L, Bosveld A, Brunstrom B, Cook P, Feely M, Giesy JP, Hanberg A, Hasegawa R, Kennedy SW, Tubiak T, Larsen JC, van Leeuwen FX, Liem AK, Nolt C, Peterson

RE, Poellinger L, Safe S, Schrenk D, Tillitt D, Tysklind M, Younes M, Waern F, Zacharewske T. Toxic equivalency factors (TEFs) for PCBs, PCDDs, PCDFs for humans and wildlife. Environ Health Perspect. 1998; 106(12):775–792. [PubMed: 9831538]

Woodrow J, Crosby D, Mast T, Moilanen W, Seiber J. Rates of transformation of trifluralin and parathion vapors in air. J Argic Food Chem. 1978; 26:6.

Yusa V, Coscolla C, Mellouk W, Pastor A, de la Guardia M. Sampling and analysis of pesticides in ambient air. J Chromatography. 2009; 1216:2972–2983.

- Chlorpyrifos-oxon is formed during air sampling with matrices containing XAD-2.
- Chemical analysis without measurement of oxon underestimates air concentrations.
- Comparisons of lab and field data suggest that oxon is present in community air.
- Accounting for chemical mixtures of parent OPs and oxons in air is important.
- Small amounts of oxon in air have a large effect on human health risk estimates.

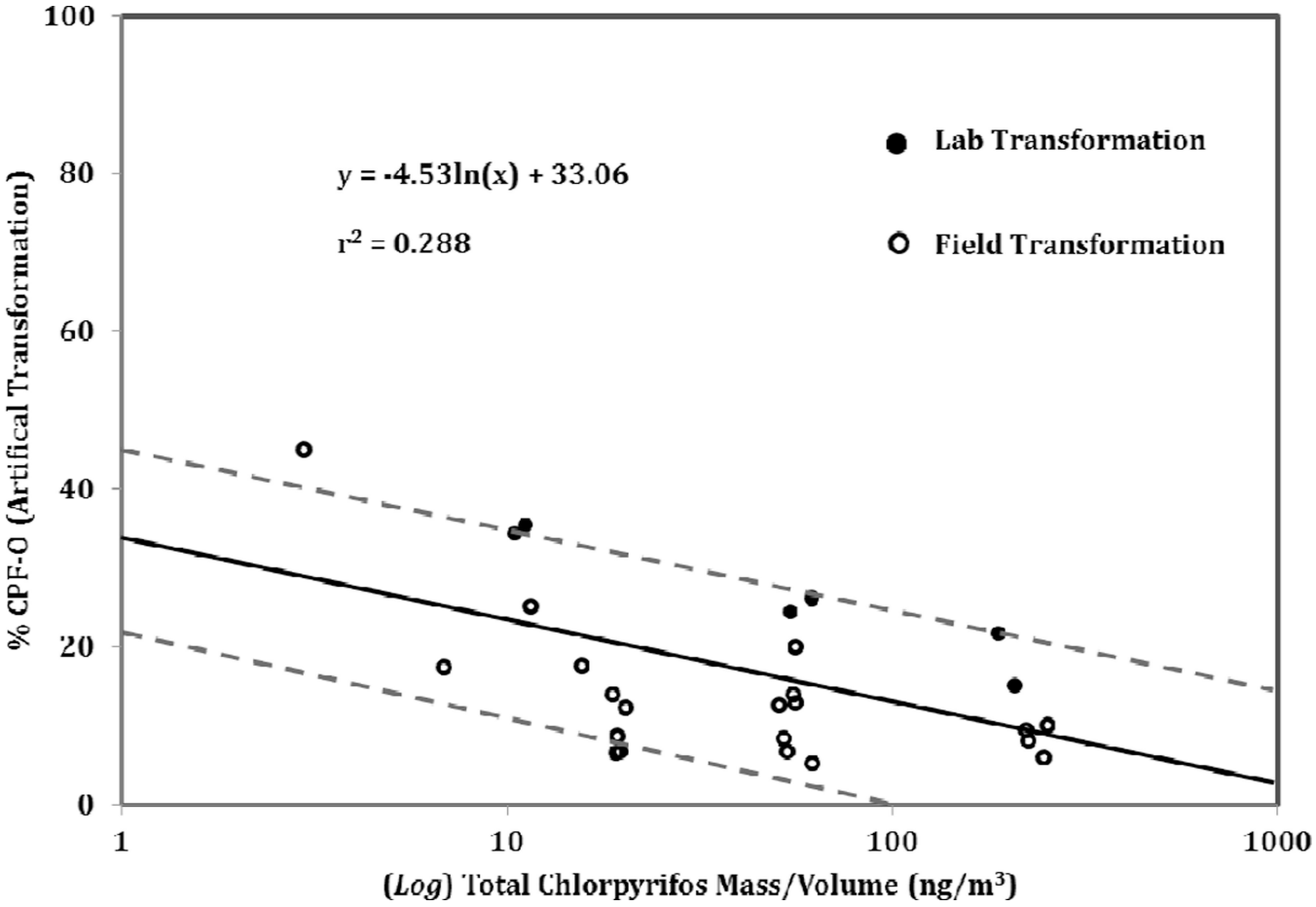

Figure 1.
% Artificial Transformation to Oxon by Log Mass per Unit Volume of Total Chlorpyrifos

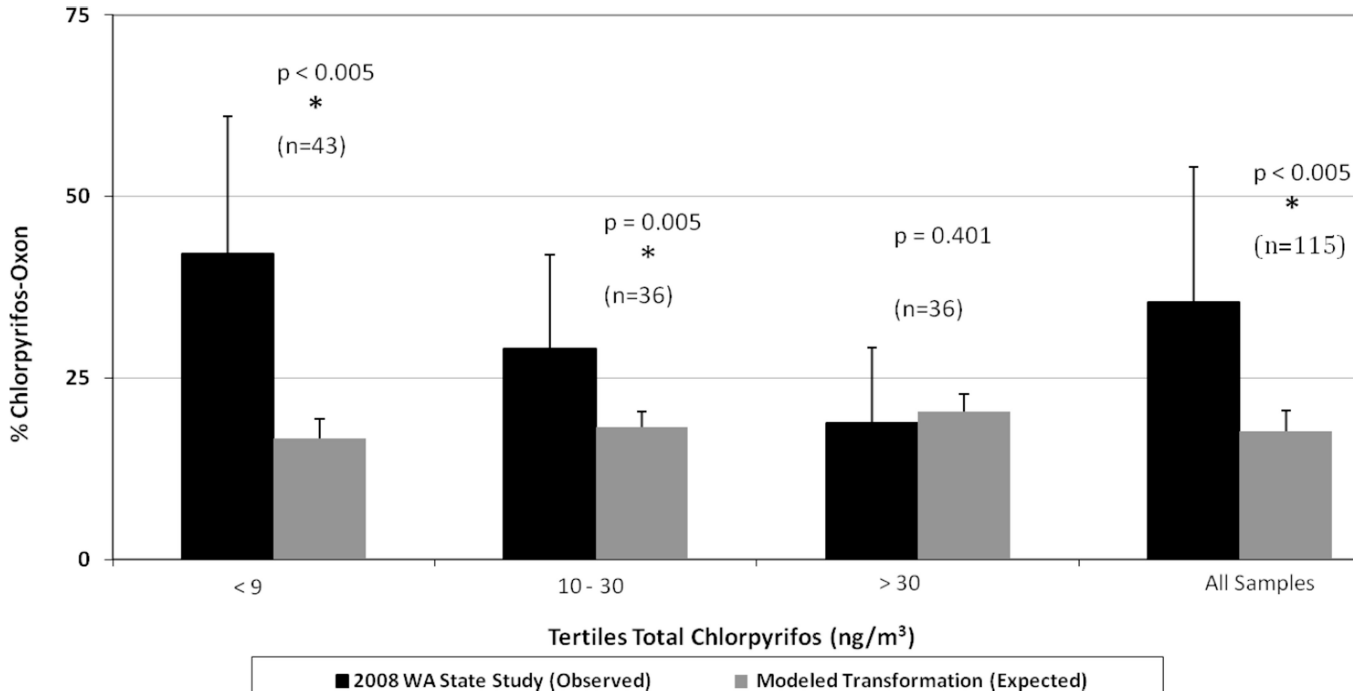

Figure 2.
Mann Whitney U-test comparing observed vs. expected % chlorpyrifos-oxon at concentration tertiles; * = p value ≤ 0.05.

Table 1

Occupational and community chlorpyrifos and chlorpyrifos-oxon air monitoring studies since 1996.

Air concentration Range >MDL[a] (ng/m^3)		Sampling location	Sampling medium	Analytical method	MDL[a]	Reference
Chlorpyrifos	**Chlorpyrifos-oxon**		**(Resin)**		**(ng/m^3)**	
Occupational Studies						
48 – 2,000	Not Measured	Iowa, North Carolina	XAD-2	LC/MS/MS	NA	Thomas et al. 2010
13,000 – 54,000	Not Measured	Egypt	XAD-2	LC/MS/MS	1.5	Farahat et al. 2010
22,000 – 56,000	Not Measured	Thailand	XAD-2	GC/FPD	1.6	Jaipieam et al. 2010
Community Studies						
10 – 230	Not Measured	Iowa	XAD-2	GC-MS	3.5	Curwin et al. 2005
16 – 1,340	16 – 230	Tulare County, CA	XAD-4	GC-MS	5.25	CARB 1998a, 1999
7 – 150	10 – 28	Parlier, CA	XAD-4	LC/MS	5	CDPR 2006, 2009
83 (Max)	8.5 (Max)	Lompoc, CA	XAD-4	LC/MS	5	CDPR 2003, 2009
1 – 2.9	Not Measured	Iowa	XAD-2	GC-MS	0.13	Peck 2005
5,000 (Max)	Not Measured	Thailand	XAD-2	GC/FPD	1.6	Jaipieam et al. 2010
9 – 494	2 – 108	Washington	XAD-2	LC/MS/MS	0.35	Fenske et al. 2009
Other Studies						
0.05 – 17.5	0.1 – 30.37	Sequoia National Park, CA	XAD-4	GC-MS	5×10^{-4}–8×10^{-4}[b]	LeNoir et al. 1999

[a] Method Detection Limit

[b] High volume sampling

Table 2

Spike masses (ng), air volume (m^3), recovery masses total chlorpyrifos (CPF), chlorpyrifos-oxon (CPF-O), and total mixture (CPF +CPF-O) (ng), % recovery total (CPF +CPF-O), and % oxon (CPF-O), in laboratory and field studies measured after 24 hour air sampling with chlorpyrifos-spiked OVS tubes. All reported values are the mean of spiked samples run in triplicates. *Italicized* recovery masses are corrected by subtracting background levels CPF and CPF-O in the outdoor environment from non-spiked samples. These corrected values were used to calculate total % recovery and % CPF-O.

Spike Mass (ng)	Sample Air Volume (m^3)	Recovery Mass (ng)			% Recovery %	CPF-O [b]
		CPF_m	$CPF\text{-}O_m$	CPF_{Total} [a] (CPF +CPF-O)	Total (CPF +CPF-O)	
Laboratory						
Low Flow Rate (2 LPM)						
0	2.81	<LOD	<LOD	<LOD	<LOD	NA
42	2.91	22	9.7	32.1	76.5	31.6
210	2.92	128	37.7	167.5	79.8	25.5
High Flow Rate (6 LPM)						
2100	8.25	1437	256.0	1706	81.2	15.4
Field [c]						
No Active Flow Rate (0 LPM) [c]						
0	0	<LOD	<LOD	<LOD	<LOD	NA
30	0	25	0	25	83.3	NA
Low Flow Rate (2 LPM)						
0 [d]	2.78	16.5	6.5	23.3	>100	30.5
15	3.03	*7.5*	*2.0*	*11.4*	76.0	18.4
30 [d]	2.88	*19.5*	*0.5*	*20.6*	68.7	2.5
60	2.86	*52.0*	*3.5*	*55.5*	92.5	6.3
200	3.2	*161.5*	*12.5*	*169.7*	84.9	7.3
High Flow Rate (6 LPM)						
0	10.1	48.5	19.5	70.96	>100	29.5
200	10.21	*150.5*	*27.0*	*177.4*	88.8	16.0
592	9.36	*482*	*44.5*	*512.4*	86.6	9.1
2628	9.58	*2118*	*151*	*2228*	84.8	7.1

[a] Total chlorpyrifos mass (CPF_{Total}, ng) is the sum of CPF and CPF-O measured in samples, adjusted by molecular weight ratio (see Equation 1 in text)

[b] % CPF-O is the amount of CPF-O divided the amount of total CPF times 100 (see Equation 2 in text).

[c] These samples had no recorded flow rate because they were deployed on a sampling tube with no sampling pump attached.

[d] Duplicate sample resulting from pump failure.

Table 3

Toxicity equivalent concentrations of chlorpyrifos for selected air concentrations after incorporation of chlorpyrifos-oxon using three toxicity equivalent factors. *Italics are > California EPA Screening Level of 1,200 ng/m^3 (CDPR 2006).*

Measured air concentration CPF (ng/m^3) [a]	Environmental oxon CPF-O (ng/m^3)[a]	Toxicity Equivalent Concentration[b] (ng/m^3)		
		5 × TEF[c]	10 × TEF[c]	100 × TEF[c]
15	2	25	36	225
25	2	35	46	235
50	11	108	165	*1203*
150	32	318	485	*3500*
250	25	381	512	*2870*

[a] Corrected for artificial transformation.

[b] TEC_{CPF} = ($CPF\text{-}O_e$ * $CPF_{MW}/CPF\text{-}O_{MW}$ * TEF) + CPF (see Equation 3 in text).

[c] TEF = Toxicity Equivalence Factor; 5-fold value from Chambers et al 1993; 10 and 100-fold values from Cole et al 2005, Sultatos et al 1982.